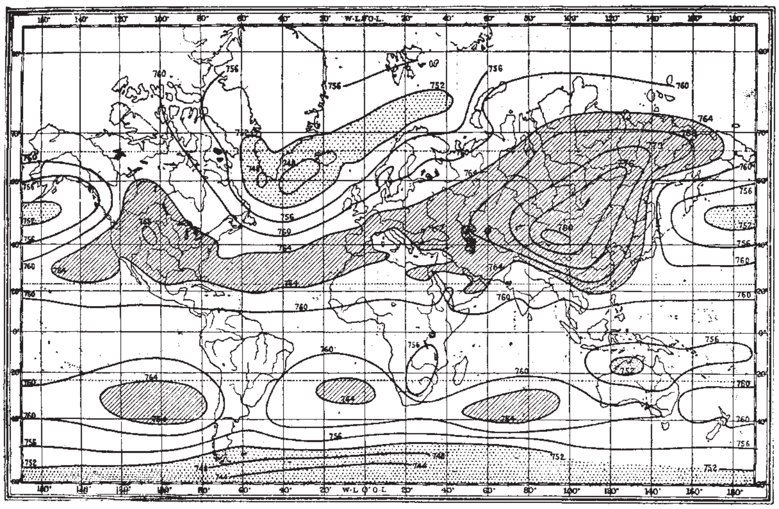
THE MECHANICS OF THE ATMOSPHERE.[1]

THE motion of the atmosphere at any time is admitted to be so complicated that any approach to a workable representation of it must necessarily be by steps. The motion at any time must be regarded as a temporary divergence from the average motion, and the question naturally arises, What is the nature of the average state of motion about which the actual state of motion fluctuates? We may approach the solution of this question in either of two ways; we may find out what the motion actually is or we may find what the forces are which, so far as we can tell, cause the motion, and trust to our knowledge of dynamics to compute the average motion from the average forces. As regards the latter method, it may be said that the dynamics of an elastic fluid moving on a rotating spheroid, however interesting, is beset with an extraordinary number of temptations to error, and the more humble ambition of trying to find out what the motion really is, although painfully laborious, has advantages which may be compared with the advantages which walking has as compared with the use of a flying machine.

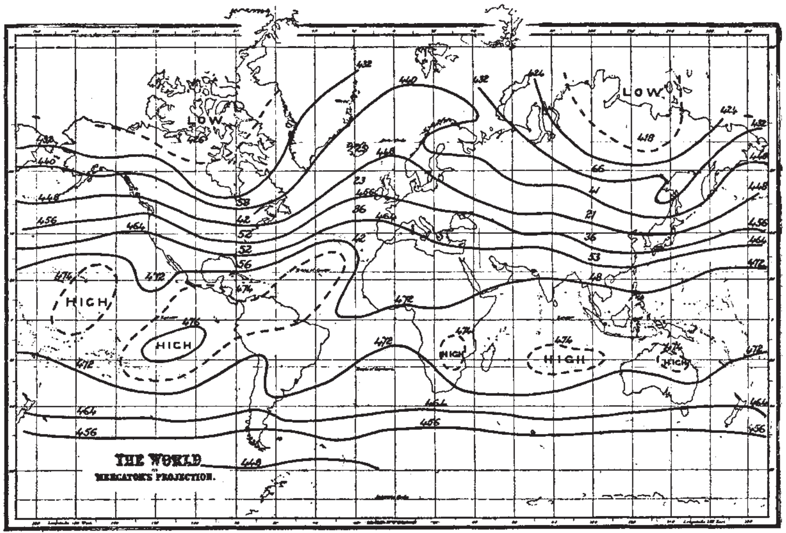
FIGURE 1. SURFACE ISOBARS FOR JANUARY.
REPRODUCED FROM HANN'S "METEOROLOGIE."



In the early 'seventies of the last century, Clerk Maxwell set a question in a Cambridge examination to which I owe the inspiration of a number of lectures and examination questions. It was this:—"Show how by observations of the motion of a body the resultant force acting upon it may be determined," and he added the luminous rider (I quote from memory), "A fish weighing 10 lb. swims through the water with a uniform velocity of 10 miles per hour, always in the same direction; find the resultant action of the water on the fish." As soon as one begins to think of answering these questions, and in particular of applying them to the relation between the controlling forces of pressure and the motion of the atmosphere, one realises what pitfalls await the unwary. The most obvious remark in relation to the first question is that the motion at any instant tells us absolutely nothing whatever about the forces acting. Unless observations sufficient to determine the change of motion have been dealt with, nothing about the cause of motion is known. Yet, in spite of this rudimentary fact of dynamics, obvious enough when it is stated, I cannot help wondering how many students of elementary dynamics ever really get rid of the notion that if you find a body moving in a certain direction you must look for a force in that direction too; we are surrounded with examples to the contrary, but the study of dynamics, being mainly deductive, usually passes them by.

In meteorology it is impossible to avoid the consciousness of temptation to the converse error of expecting to find the motion of air in the direction of the recognised forces. The most obvious force is that due to pressure, and who can resist the temptation of thinking that the flow of air from a high-pressure area to a low-pressure area must be the dominant feature of atmospheric motion? Yet the one great inductive statement in connection with meteorology, Buys Ballot's law, warns us that if we trust to the direction of forces to indicate the direction of motion we shall certainly be misled. Motion along isobars, perpendicular to the gradient, is a closer representation of the actual state of things than motion along the gradient, along, that is to say, the direction of resultant forces.

FIGURE 2. ISOBARS AT THE LEVEL OF 4000 METRES FOR JANUARY.
FROM HANN'S REPRODUCTION OF THE ORIGINAL DIAGRAM BY TEISSERENC DE BORT.



Pressures in millimetres: velocities in miles per hour, corresponding to the acceleration for different gradients resulting from the Earth's rotation.

There is no doubt that if we could arrest for a time the motion of the atmosphere, without altering the pressure, and let the air start again from rest, the direction of initial motion would be along the pressure gradients from high to low, but we have to deal with an atmosphere that has been moving for countless ages, and all that existing forces do is to maintain or disturb the average, or steady motion; if in those circumstances we find the motion taking place in the direction of the forces, we find a condition of things which ought not to be expected, and one which requires explanation.

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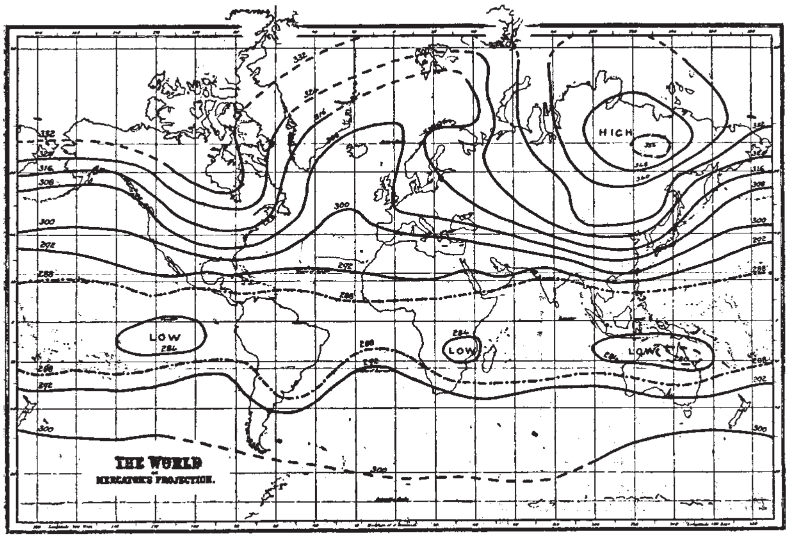
[1] Based upon a paper on the "General Circulation of the Atmosphere in Middle and Higher Latitudes," read before the Royal Society on June 2 by Dr. W. N. Shaw, F.R.S.

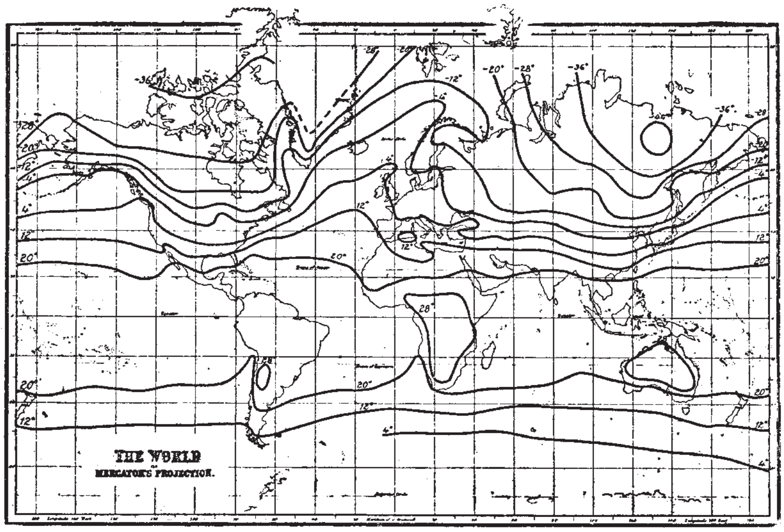
The question arises as to what one ought to expect the steady motion to have become in course of time. To afford some idea of the answer to this question, let me refer to the four diagrams here reproduced. The first gives the average isobars for January at the earth's surface, and discloses no simple representation of steady conditions. There are the well known high-pressure areas about the tropics, and isolated regions of low pressure over the North Atlantic and Pacific; but when we look at Fig. 2, the isobars computed by Teisserenc de Bort for the 4000-metre level, there is an indication of comparatively simple steady motion, namely, a motion round the polar axis from west to east, somewhat deviated, however, to south or north by land or sea areas. Now if we assume that the motion is along the isobars thus represented, so that the lines of the diagram practically represent lines of flow of air, we must remember that the motion on a rotating earth implies a certain normal acceleration of the air to keep it in its path, just as the bob of a conical pendulum requires an acceleration towards its equilibrium position to maintain its motion in a circular path. The effective horizontal acceleration of the air is $2\omega V \sin \lambda$, where ω is the angular velocity of the earth, V the velocity of the wind, and λ the latitude.

FIGURE 3. MEAN PRESSURE DUE TO THE WEIGHT OF THE STRATUM OF THE ATMOSPHERE BELOW 4000 METRES. FOR THE MONTH OF JANUARY. COMPUTED FROM FIGURES 1 AND 2. PRESSURES ARE GIVEN IN MILLIMETRES.



Of the velocity at the 4000-metre level we can only form an idea from the observed motion of clouds, and, so far as we know, the only forces available to give the necessary acceleration are those due to the pressure distribution which Teisserenc de Bort has plotted. By equating the pressure gradient to the product of the density and acceleration we can determine V, and the values thus computed are shown in miles per hour by figures between the isobars on the diagram. They must not be confused with the pressures, which are given in millimetres. The average wind velocities thus computed are not at all unreasonable, and it follows that motion along Teisserenc de Bort's isobars at about 50 miles per hour is not at all an unreasonable representation of the average steady motion of the atmosphere at that level in the month of January. That the directions of motion are appropriate is confirmed by Hildebrandsson's report on cloud motion to the International Meteorological Committee.

FIGURE 4. MEAN TEMPERATURE AT THE EARTH'S SURFACE. FOR THE MONTH OF JANUARY. IN CENTIGRADE DEGREES.



So much for the upper air; the motion is comparatively simple. Then it might be supposed that the complexity of the surface motion is due to extreme complexity of pressure in the lower stratum. The pressure due to the weight of the lower stratum is shown in Fig. 3, which gives the pressure differences between Figs. 1 and 2. There is, strange to say, no more complexity about this distribution than there is about the pressure of the upper layer; in fact, the lines of the two are extraordinarily similar, only the pressure gradients run in opposite directions. Writing "high" for "low," the one diagram would not be an unsatisfactory duplicate of the other, except that the lower stratum has a dislocation of the pole of high pressure from the geographical pole to north-eastern Siberia. Applying the same principle of motion to this diagram as to Fig. 2, it would represent, with suitable velocities calculated in a similar manner, a circulation from east to west in each hemisphere round the pole of cold.

Compare both these diagrams with Fig. 4, representing the surface isothermal lines—the similarity is again conspicuous. The intervals are for every 8° C. of temperature instead of 8 mm. of pressure, and speaking broadly of the temperate latitudes, starting from a suitable datum temperature or pressure, the lines might be interchanged, a step of one degree of temperature (Fig. 4) corresponding to a step of one millimetre of pressure in the same direction for the upper layer (Fig. 2), and in the opposite direction for the lower layer (Fig. 3).

The complexity of the surface pressure arises, therefore, not from the upper layer alone, nor from the lower layer alone, but from the superposition of the two. We can resolve the surface pressure into two components, one due to the upper stratum above 4000 metres which, if it acted alone, would produce a general circulation from west to east around minima of pressure near the poles; the other, due to the lower stratum, which, if it acted alone, would produce a circulation from east to west. Both circulations would correspond closely with the surface distribution of isotherms. Where the one is predominant, in the lower middle latitudes, we get resultant westerly circulation; where the other is predominant, near the poles of cold, we get an easterly circulation. Between the two we get a region of minimum pressure and a merging of the two circulations which gives rise to the circular storms of the northern and southern temperate zones.

It appears, therefore, that we ought to regard the surface distribution of temperature as giving rise to a distribution of pressure in the lower stratum tending to maintain a circulation of air from east to west round the poles of cold. Extending this idea, a region of cold in the northern hemisphere should tend to maintain a clockwise circulation round its centre in the lower atmosphere, and a region of heat a counterclockwise circulation.

The reciprocity between the pressure distribution of the upper and lower layers is of course not fortuitous. Hann has shown that the expansion of the lower layer by heat increases the pressure at a given level in the upper regions, without altering the pressure at the surface, by the mere thrusting of part of the air upwards; so that the observed effect of expansion over a large area is to diminish the pressure of the lower stratum and increase, by an equal amount, that of the upper. Referring to the diagrams again, the effect of increased surface temperature upon the isobars of Fig. 3 would be a bulge of the isobars towards the region of low pressure—the equatorial regions; upon the upper isobars there would be a corresponding bulge towards the region of higher pressure, again the equatorial regions. Thus the lines of both diagrams would be affected geographically in an exactly similar way and to the same extent; they would thus preserve their similarity in spite of temperature variations at the surface.

It would be interesting to consider what the effect of the daily solarisation of the earth should be from this point of view. Primarily it should produce no pressure variation at the surface; but inequalities of motion in the upper and lower air would probably alter the relative phase or magnitude of the disturbance of the two components, and hence give rise to daily variations of pressure at the surface, and thus necessarily produce a diurnal variation of the barometer.

Other consequences follow from the treatment of the distribution of pressure due to the weight of the lower layer as producing, or rather maintaining, a circulation in the one direction or the other about the colder or warmer regions, as the case may be, instead of flow from cold regions to hot.

One important result as regards the formation of circular storms in our latitudes may be inferred from this method of analysing the distribution of surface pressure. Friends have frequently suggested to me that our circular storms are like the eddies formed when water flows through a bridge; and to them I have always put the question, What in the atmosphere stands for the bridge? I am now prepared to recognise that the caps of relatively cold air in the north and south polar regions form an adequate representation of the piers of the bridge. In the lower air, where the pressures of the polar caps are dominant, they stop the westerly currents which still flow in lower latitudes, and replace them by currents from the east. Between these two currents is a field where mixing must take place, and circular eddies may be formed.

What happens in the equatorial regions is another story. Buys Ballot's law shows that the equator is subject to a peculiar meteorological condition. If you stand with your back to the wind north of the equator, the low barometer is on your left; south of the equator, it is on your right. There must be a transition region where the law ceases to apply, as, indeed, one would expect if Buys Ballot's law is the practical expression of motion with an acceleration due to the rotation of the earth, and varying as the sine of the latitude.

In the upper air of the equatorial regions there is probably a persistent flow from the east, as shown by observations of clouds and of the Krakatoa dust. In respect of the formation of eddies, this current will act like an intermediate pier of a bridge. Hence, in January, the river in which, upon this analogy, atmospheric eddies may be expected is a stream of air flowing round the earth in middle latitudes, divided by the equatorial belt with its region of doldrums below and easterly current above, and bounded north and south by easterly currents which correspond with the circulation of the lower atmosphere induced by the predominant influence of the polar caps of cold air. Eddies may be looked for between the easterly and westerly currents, and they are sometimes found there.

W. N. SHAW.

NOTES.

THE trustees of the Carnegie Institution met on May 18 and transacted the necessary business to provide for the transfer of all matters to the Carnegie Institution of Washington, a charter for which passed Congress and was approved on April 28. The trustees named in the Act met at once and reorganised under the new charter. The by-laws of the Carnegie Institution were adopted as the by-laws of the new organisation, and the officers of the old organisation were elected. General resolutions adopting all the obligations, &c., of the old institution were passed. Under the new charter no questions can be raised as to the competency of the institution to carry on the operations outlined in the deed of gift of the founder. The executive committee of the Carnegie Institution of Washington met after the reorganisation, and practically completed the making of grants for the year 1904. It will greatly facilitate the work of the executive committee if all those thinking of making applications for grants for 1905 will do so not later than September, as applications for grants for 1905 will then be taken up.

A SLIGHT but decided earthquake, which lasted about a second, was experienced at Derby at 3.22 p.m. on July 3. The vibration was not nearly so pronounced as on the occasion of the seismic disturbance a year ago. A similar shock was felt in the mid-Cheshire district about the same time. In Leftwich, near Northwich, the tremors were very distinct. The shock, which was also felt in Northwich, lasted two seconds, and at Sandbach four seconds. Two shocks